MAGNETIC SENSOR FOR DETECTION OF GROUND VEHICLES BASED ON MICROWAVE SPIN WAVE GENERATION IN FERRITE FILMS

A. Slavin*, and V. Tiberkevich
Department of Physics, Oakland University, Rochester, MI 48309

E. Bankowski
Survivability Technology Area, TARDEC, RDECOM, Warren, MI 48397-5000

ABSTRACT

We propose to use the magnetic signatures, formed either by the residual magnetization or by deformation of the local Earth's magnetic field by large metal masses, for distant detection of ground vehicles. Measuring this weak magnetic field would allow one to determine the position, type, and velocity of the vehicle. Wirelessly transmitting data from the net of such detectors and processing the obtained information at the central processing computer will enable one to determine the number of ground vehicles and their individual characteristics in a group. The problem of vehicle detection is of great importance for both the combat and civil applications. The usual radio and microwave frequency radar technologies, which are successfully used for the detection of flying objects, have a limited application for the solution of this problem, due to a strong noise signal created by other surface objects (like buildings and trees) and by the Earth surface itself. The proposed magnetic sensor will not be affected by the weather conditions, such as snow, fog, or rain. It can be used in urban setting.

1. INTRODUCTION

The problem of distant detection of ground vehicles, determination of their type, velocity, and direction of propagation is of great importance for both combat and civilian applications. The usual radio and microwave frequency radar technologies, which are successfully used for the detection of flying objects, have a limited application for the solution of this problem, due to a strong noise signal created by other surface objects (like buildings and trees) and by the Earth surface itself. On the other hand, optical methods that could be used as alternative technology are very sensitive to the weather conditions and can not be used at night time and/or under the conditions of strong snow, fog, or rain. Any of the usual methods of distant detection can not be used in city conditions. Therefore, alternative systems of distant detection of ground vehicles need to be developed.

One of the perspective methods of the distant detection of ground vehicles is based on the magnetic properties of Fe-based alloys, which form the main part of the mass of a ground vehicle. Alloys of ferromagnetic metals always have some residual magnetization, which creates a weak constant magnetic field in the outer space. Even in the practically almost impossible case of fully demagnetized metal, a ground vehicle made of this metal has a large magnetic permeability and deforms locally the magnetic field of the Earth. Such a deformation of the constant Earth's magnetic field can be detected and can be used as a “magnetic signature” of a ground vehicle. At the same time other ground objects, as well as the Earth’s surface itself, are magnetically transparent and, therefore, do not create their own magnetic signal and do not interfere with the magnetic signal created by a ground vehicle.

Detection of such *magnetic signatures* of ground vehicles can be performed in any weather and in the most complicated urban conditions. Creation of constant magnetic fields in large volumes by other methods is rather difficult, and, therefore, the detection of magnetic signatures of ground vehicles provides reliable information about their presence.

2. DETECTION OF GROUND VEHICLES BASED ON MICROWAVE SPIN WAVE GENERATION IN FERRITE FILMS

2.1 Technical Approach

To detect a weak magnetic field created by the ground vehicle (or a deformation of the constant magnetic field of the Earth caused by the same vehicle) , we propose to use the phenomenon of the Larmor precession of a magnetic moment (e.g., electron’s spin) in an external magnetic field. The frequency ω of such a precession linearly depends on the magnitude of the constant magnetic field H, $\omega = \gamma H$, where $\gamma \approx 2\pi \cdot 2.8$ MHz/Oe is the gyromagnetic ratio. Due to the large value of γ and possibility of extra precise measurement of the frequency one can easily measure magnetic fields as small as parts of micro Oersted that is several orders below the magnitude of the constant Earth’s magnetic field.

To reduce the spurious influence of the magnetic dissipation, which is responsible for the finite linewidth of the precession frequency line in any passive circuit

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 NOV 2006	**N/A**	-

4. TITLE AND SUBTITLE **Magnetic Sensor For Detection Of Ground Vehicles Based On Microwave Spin Wave Generation In Ferrite Films**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Physics, Oakland University, Rochester, MI 48309**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002075.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

containing ferromagnetic resonance element, we propose to measure the magnetic-field-dependent generation frequency in an active ring containing a magnetized ferromagnetic film.

The principal scheme of the proposed device for the measurements of weak magnetic fields is shown in the Fig. 1. The device consists of the wide-band amplifier with the ferromagnetic yttrium-iron garnet (YIG) film in the feedback loop. The device represents the usual auto-oscillator with generation frequency controlled by the dispersive characteristics of the ferromagnetic delay line, which are very sensitive to the external magnetic field. The use of a generating active ring strongly decreases the influence of the dissipation processes and narrows the bandwidth of generated resonance frequencies in the circuit. The analogous scheme of the microwave circuit for the generation of ultra-short high-power pulses was proposed by one of the investigators in (Kalinikos and Slavin, 2001).

The sensitivity of the proposed detector can be improved using the bridge circuit, schematically shown in the Fig. 2. The modified device consists of two identical ferromagnetic film oscillators, one of which (generator B at the Fig. 2) is magnetically shielded.

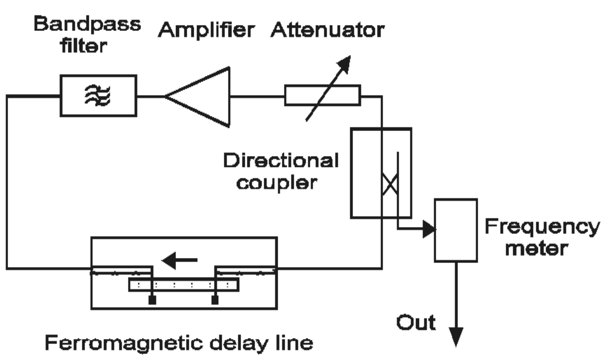

Fig.1. Scheme of the device for measuring weak constant magnetic fields. The device represents a microwave oscillator and consists of a wide-band amplifier with a ferromagnetic delay line in the positive feedback loop. The bandpass filter is used to guarantee the single-mode operational regime of the oscillator. The tunable attenuator controls the generation power. The part of the generated signal is taken out of the active ring by the directional coupler and its frequency is measured by the frequency meter.

The output microwave signals from both oscillators are supplied to the frequency mixer, which generates the sum $\omega_A + \omega_B$ and difference $\omega_A - \omega_B$ frequencies (here ω_A and ω_B are the generation frequencies of the oscillators A and B, respectively). The low-frequency filter cuts off the high-frequency component $\omega_A + \omega_B$ and the frequency meter determines the low-frequency signal $\omega_A - \omega_B$. Due to the magnetic shielding of the generator B, the generated frequency ω_B does not depend on the weak magnetic field H, created by a vehicle. Thus, the device, shown in the Fig. 2, directly measures the small deviations of the frequency of generation $\omega_A - \omega_B \approx (\partial\omega/\partial H)H$.

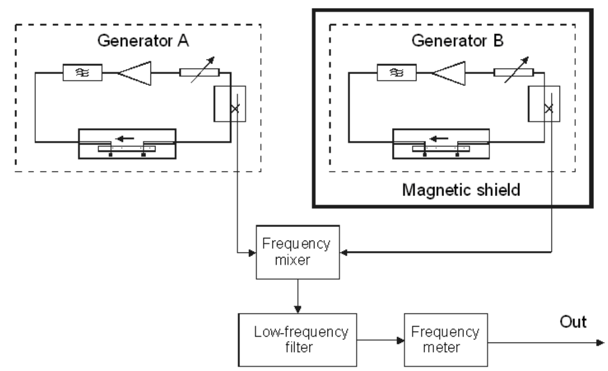

Fig. 2. Bridge circuit with two identical microwave oscillators A and B, one of which (oscillator B) is magnetically shielded. The output signal from both generators is supplied to the frequency mixer, which generates signals at the sum $(\omega_A + \omega_B)$ and difference $(\omega_A - \omega_B)$ frequencies. The high-frequency component $\omega_A + \omega_B$ is filtered out by the low-frequency filter, and the frequency of the low-frequency signal $\omega_A - \omega_B$, proportional to magnetic field, created by a vehicle, is measured by the accurate frequency meter.

Our main task is to develop an engineering theory of operation of the proposed devices and to estimate their working parameters.

2.2 Theoretical Model

To estimate the minimum magnetic field $H_{\min}$ which can be detected by the proposed scheme and maximum vehicle detection distance $L_{\max}$ we will consider a simple model of the ferromagnetic delay line oscillator, neglecting the crystallographic anisotropy of the ferromagnetic material and assuming that both bias magnetic field H_0 and magnetic field created by a vehicle ΔH lie in the film plane along the length of the film. In this geometry frequency $f(H, k)$ of the spin wave with wave number k is given by

$$f\left(H,k\right)=\frac{\gamma}{2\pi}\sqrt{H\left(H+4\pi M_0 P_k\right)},$$

where $\gamma/2\pi$ = 2.8 MHz/Oe is the gyromagnetic ratio, M_0 is the saturation magnetization of the ferromagnetic material, and

$$P_k = \frac{1-e^{-kd}}{kd},$$

where d is the thickness of the film.

The allowed values of the wave number k in delay line oscillator are given by

$$k_n = \frac{2n\pi}{l},$$

where l is the length of the active part of the film. In typical experimental situation $d \approx 5-10$ μm, while $l \approx 1-5$ mm, so $k_n l << 1$ and, with accuracy, sufficient for rough estimates, one can assume $P_k \approx 1$.

The frequency difference $\Delta f = f_A - f_B$, generated in the proposed bridge scheme (see Fig. 2), is equal to

$$\Delta f = f(H_0 + \Delta H, k) - f(H_0, k) \approx \frac{\partial f}{\partial H}\Delta H .$$

Then the minimum detectable magnetic field $H_{\min}$ can be estimated as

$$H_{\min} = \frac{\Delta f_{\min}}{(\partial f/\partial H)} \approx \frac{2\pi}{\gamma}\frac{\sqrt{H_0(H_0+4\pi M_0)}}{H_0+2\pi M_0}\Delta f_{\min},$$

where $\Delta f_{\min} \approx 1$ Hz is the minimum frequency difference that can be measured by the frequency meter.

Using typical values for high-quality magnetic films of yttrium-iron garnet (YIG) $4\pi M_0 = 1750$ Oe, $H_0 = 100$ Oe we obtain the estimate for the minimum detectable magnetic field $H_{\min} \approx 0.16$ μOe, which is about 10^7 times smaller than the natural Earth magnetic field.

To estimate the maximum vehicle detection distance $L_{\max}$, we consider the distortions of the magnetic field, created by the vehicle, as a field from the magnetic dipole

$$M = (\mu - 1)H_E V,$$

where $\mu \approx 100$ is the magnetic susceptibility of the Fe-based alloys, $H_E \approx 0.2$ Oe is the Earth's magnetic field, and $V \approx 0.1$ m^3 is the total volume of metallic parts of the vehicle. Here we assumed that the vehicle has no residual magnetization, and the only magnetic field created by the vehicle is due to the distortions of the Earth's natural magnetic field. Under this assumption we estimate the *lower* limit of the detection distance $L_{\max}$.

Neglecting angular dependence of the magnetic dipolar field, one can estimate the magnetic field at the distance L from the vehicle as

$$\Delta H(L) \approx \frac{M}{L^3}.$$

Condition $\Delta H(L_{\max}) = H_{\min}$ determines the maximum detection distance

$$L_{\max} = \left(\frac{(\mu-1)H_E V}{H_{\min}}\right)^{1/3} \approx 230 \text{ m}.$$

We believe that this detection distance can be increased by several times using the optimized values of the device parameters. Even such non-optimized estimation, however, clearly shows that the proposed method of vehicle detection can be very useful in typical urban conditions, when other methods of ground vehicle detection can not be used at all.

2.3 Research Preceding and Leading to This Project

During the last 10 years we conducted research in the field of linear and non-linear properties of spin waves in thin magnetic films. A number of new physical phenomena was discovered and investigated, for instance, relaxation reversal by frequency-selective amplification (Melkov et al., 2001) and self-generation of two-dimensional bullets (Serga et al., 2004). A great attention was paid to the practical application of our scientific results. Using yttrium-iron garnet (YIG) as a medium for spin wave propagation, we developed engineering theory and experimentally tested (in collaboration with the experimental group from Kiev National University, Kiev, Ukraine) several devices for processing of short ($\tau \sim 10-20$ ns) pulsed signals in microwave frequency range ($f \sim 5$ GHz, $\lambda \sim 6$ cm) (see (Melkov et al., 2003) and references therein). Among the proposed devices are such non-trivial functional devices as extremely efficient microwave signal convolver (Kobljanskyj et al., 2002a) and controlled delay line with possibility of time-profile reversion (Kobljanskyj et al., 2002b) and (Melkov et al., 2000). We also found a way to use short-wavelength dipole-exchange spin waves (DESW) for information processing at microwave frequencies (Kobljanskyj et al., 2003).

The proposed scheme of the microwave generator with a ferromagnetic film in the feedback loop (see Fig. 1) has been studied before in the context of one- and two-dimensional soliton auto-generation (Serga et al.,

2004). An approximate theory that takes into account only the main magnetic interactions in the ferromagnetic film, of the linear and non-linear microwave generation in such a device was successfully developed. The analogous scheme with Sc-doped hexagonal Ba-ferrite ferromagnetic film was proposed for high-power ultra-short pulse generation in the millimeter wave frequency range, and the technical characteristics of the corresponding device were calculated (Kalinkos and Slavin, 2001).

3. CONCLUSION

3.1 Innovation

The proposed new technology will increase the possibility of distant detection of ground vehicles by use of an additional source of information, namely, magnetic signatures of large metal masses. The proposed technology is insensitive to weather conditions and can work in extremely hard landscapes (say, in city conditions), when other methods of distant detection fail to provide any useful information.

3.2 Relevance

The proposed technology has application for the distant detection and identification of ground vehicles using their magnetic signatures.

3.3 Transition of Research

The proposed new technology could be potentially applied in homeland defense and automotive industry.

4. REFERENCES

Kalinikos, B. A. and Slavin A.N., 2001: "Generation of short millimeter-wave radio pulses using solitons in ferrite-based active rings", Appl. Phys. Lett. **79**, 1576-1579-1582.

Kobljanskyj, Yu. V., Melkov, G. A. Serga. A. A., Tiberkevich, V. S. and Slavin, A. N., 2002: "Effective Microwave Ferrite Convolver using a Dielectric Resonator", Appl. Phys. Lett. **81**, 1645-1647.

Kobljanskyj, Yu. V., Melkov, G. A., Serga. A. A., Tiberkevich, V. S. and Slavin, A. N., 2002: "Active Magnetostatic Wave Delay Line for Microwave Signals", IEEE Trans. Magn. **38**, 3102-3105.

Kobljanskyj, Yu. V., Melkov, G. A. Serga. A. A., Tiberkevich, V. S. and Slavin, A. N., 2003: "Microwave Signal Processing using Dipole-Exchange Spin Waves", J. Appl. Phys. **93,** 8594-85898 .

Melkov, G. A., Kobljanskyj, Yu. V., Serga, A. A., Tiberkevich, V. S. and Slavin A. N., 2001, "Reversal of Momentum Relaxation", Phys. Rev. Lett. **86**, 4918-4921.

Melkov, G. A., Kobljanskyj, Yu. V., Slavin A. N. and Tiberkevich, 2003: "Signal Processing In A Ferrite Film Using Parametric Pumping", Journal of Communications Technology and Electronics **48**,119-124.

Melkov, G. A., Serga, A. A., Tiberkevich, V. S., Oliynyk, A.N. and Slavin, A. N., 2000: "Wave Front Reversal of a Dipolar Spin Wave Pulse in a Non-Stationary Three-Wave Parametric Interaction", Phys. Rev. Lett. 84, 3438-3441.

Serga, A. A., Demokritov, S. O., Hillebrands, B. and Slavin A. N., 2004: "Self-Generation of Two-Dimensional Spin-Wave Bullets in Magnetic Films", Phys. Rev. Lett. **92,** 1723-1726.